From a mine to you –
Sustainability of the Finnish mining sector in the context of global supply chains of metals

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ACADEMIC DISSERTATION
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Cover photo: Colourful oxidation marks on an old Outukumpu mine wall form nowadays part of an outdoor museum.

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Abstract

The metal mining industry has experienced a marked boom in Finland since the beginning of the 21st century, driven by the general rise in the price levels of base metals, iron and gold, in particular. The boom started with increased exploration and mine development activity, and from 2007 onwards has increased the mined ore levels to all-time highs.

Before the current boom, the industry had been suffering a gradual downturn during the 1990s, and was considered as a minor branch in the economic structure of the country. Furthermore, the strong domestic metals industry started to lean increasingly on imported mineral raw materials.

The rapid growth in exploration and mining activity in the country has now raised expectations of increased socio-economic benefits, but also fears of environmental degradation and negative effects on other lines of business, such as nature tourism. Reflecting this, the mining industry has already faced more intensive opposition than ever in its history in Finland. The opposition reflects the changed values of civil society in Finland in the 21st century, and the expectations towards the good environmental and socio-economic performance of the mining industry.

In this thesis study, the future directions of the Finnish metals mining industry and the related environmental and expected socio-economic effects were examined, as well as the trade of minerals to Finland and its environmental effects and governance context in origin countries. The focus was also on considering the environmental pressures and material flows of production chains of metals (e.g. life cycle assessment and material flow analysis), and on investigating the roles of governance, industry and academia in striving towards increased sustainability of the metal mining industry in Finland.

The results suggest that in the context of international production chains of metals in Finland, the environmental pressures abroad related to mining and mineral processing are higher than domestic pressures. However, the domestic effects are increasing, as the mining industry in Finland will most probably continue to grow in the future. This growth has the potential to bring socio-economic prosperity to the country, but also increases in environmental pressures. In reaching towards a more sustainable mining industry, the co-operation between governance, industry and academia has to be profound. Environmental protection has to be strengthened and preventing further environmental accidents in mines needs to be the key goal. Further developments in environmentally sound mining and processing technologies will help to both steer environmental performance and enhance the competitiveness of the Finnish mining technology branch. Additionally, transparent CSR and communication strategies in mining companies will help to raise common knowledge and acceptance of mining. Finally, careful legislation and solid project feasibility planning support the continuation of mining activity in a climate of economic fluctuation.

Tiivistelmä (In Finnish)

Yleinen metallien hintojen nousu 2000-luvun alkupuoliskolla on johtanut kaivostoiminnan kasvuun Suomessa. Alkuvaiheessa lisääntyi erityisesti kiinnostus malminetsintää kohtaan ja vuodesta 2007 alkaen uusien kaivosten vaikutuksesta kasvu on näkynyt myös kaivostoiminnan konkreettisena kasvuna. Ennen 2000-luvun vaihdetta kaivosteollisuus oli laskusuhdanteinen ala, jonka kansantaloudellinen merkitys oli pieni. Kotimaisten kaivostuotteiden saatavuuden vähyyden vuoksi myös metalliteollisuus turvautui yhä enemmän ulkomailta tuotuihin mineraaliraaka-aineisiin.

Kaivostoiminnan nopea kasvu on nostanut odotuksia kasvavista yhteiskunnallisista ja taloudellisista hyödyistä, mutta myös pelkoa mahdollisten ympäristöhaittojen laajuudesta. Myös mahdolliset muihin elinkeinoihin, kuten matkailuun ja porotalouteen, kohdistuvat vaikutukset ovat olleet esillä, ja kaivostoiminta onkin viimeaikoina kohdannut Suomessa määrätietoisempaa vastustusta kuin ennen. Vastustus heijastaa 2000-luvun suomalaisten muuttunutta arvomaailmaa sekä kaivostoiminnan ympäristö- ja yhteiskuntavastuun toteutumisen tärkeyttä tässä yhteydessä.

Tässä tutkimuksessa pyrittiin selvittämään suomalaisen metallikaivostoiminnan ympäristösekä yhteiskunnallisten vaikutusten laajuutta tulevaisuusperspektiivissä. Lisäksi tarkasteltiin ulkomailta Suomeen tuotujen mineraalirikasteiden tuotantoketjun ympäristövaikutuksia sekä hyvän hallinnon toteutumista tuottajamaissa. Tarkastelun kohteena oli myös tuotantoketjujen ympäristövaikutusten arvioinnin metodiikka kohdistuen erityisesti elinkaariarviointiin ja materiaalivirta-analyysiin, sekä hallinnon, kaivosteollisuuden ja tiedemaailman roolit metallikaivostoiminnan kestävän kehityksen edistämisessä.

Tulosten perusteella vaikuttaa siltä, että Suomessa jalostettavien mineraaliraaka-aineiden hankinnasta aiheutuvat ympäristöhaitat ovat suuremmat ulkomailla kuin Suomessa, pohjautuen suomalaisen metalliteollisuuden voimakkaaseen riippuvuuteen tuontiraaka-aineista. Kaivostoiminnasta Suomessa aiheutuvat kokonaisympäristövaikutukset ovat kuitenkin kasvaneet selvästi 2010-luvulle tultaessa ja tulevat todennäköisesti edelleen kasvamaan, jos nykyinen kehitys kaivostoiminnassa jatkuu. Toisaalta toiminnan kasvu luo edellytyksiä myös työllistymiselle ja yleiselle taloudelliselle toimeliaisuudelle erityisesti Itä- ja Pohjois-Suomessa.

Kaivostoiminnan mahdollinen kasvu tuo siis potentiaalisesti sekä yhteiskunnallisia hyötyjä että kasvavaa painetta ympäristöä kohtaan. Jotta tästä kasvusta saataisiin mahdollisimman suuri hyöty mahdollisimman vähäisin haitoin, on kiinteä yhteistyö hallinnon, kaivosteollisuuden ja tiedeyhteisön välillä välttämätöntä. Ympäristön suojelu ja onnettomuuksien välttäminen on keskiössä, mutta myös kaivos-, rikastus- ja jalostusteknologian jatkokehitys parantaa kaivosteollisuuden toimintaedellytyksiä. Läpinäkyvyyden ja kommunikaation vahvistaminen auttavat yleisen tiedon kasvattamisessa ja kaivostoiminnan sosiaalisen toimiluvan vahvistamisessa ja huolellinen lainsäädäntö sekä kannattavuusarvioinnit kaivostoiminnan jatkuvuuden turvaamisessa vaihtelevassa taloudellisessa ympäristössä.

Preface

The research for this thesis started at the beginning of 2008 with co-funding from the Academy of Finland through the Graduate School of Geology and the Geological Survey of Finland (GTK). The work started at GTK facilities in close collaboration with the "Mineral Raw Material Flows and Sustainable Utilisation" (MIRA) project. The project goals were to develop the use of geological variables in life cycle assessment and research on material flow, to assess the environmental and economic impacts of mining and quarrying, and to offer support to decision making on these issues. At a later stage, collaboration with the Thule Institute at the University of Oulu and the Finnish Environment Institute diversified the research outcomes of this thesis.

Between 2008 and the present, the activities of the mining industry in Finland have grown significantly, bringing into focus environmental and social matters and strong opposition, and challenging the legacy of mining in the country. This has prompted discussions on the performance of the mining industry and the role of governance, and triggered multiple seminars and research projects considering the current practicalities, performance and status of the mining industry in Finland. This thesis has grown and taken shape alongside this transition, and benefitted greatly from discussions with different actors in the field.

Acknowledgements

I would like to warmly thank the Geological Survey of Finland (GTK) and the Graduate School of Geology for financially supporting this work. My gratitude also goes to GTK for providing the excellent research conditions and overall support for this thesis research. In particular, I would like to thank regional director Keijo Nenonen for your patience and trust in me to succeed in this research!

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Finally, I would like to thank Susanna Kihlman from GTK for your peer support during this process. Your presence and spurring has meant a lot to me. Also, my thanks go to the people in the bedrock and the mineral resources section (and other people in the shared coffee room!) at GTK for your guidance in multiple mineral-related aspects. Some of you are also remembered for your bitter comments over my branch of research. And many warm thanks go to Sami Tolppanen at the GTK library for your excellent support in article and book hunting across the globe, as well as to Harri Kutvonen at GTK for helping to get this work between the shelves.

List of tables and figures

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Abbreviations

AMD	Acid mine drainage
BE	Best estimate scenario
BL	Base-level scenario
CO_{2eq}	CO_2 emission equivalent
CPI	Corruption Perception Index
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CSR	Corporate social responsibility
EITI	Extractive Industries Transparency Initiative
EPI	Environmental Performance Index
EU	European Union
GEMIS	Globales Emissions-Modell integrierter Systeme
GHG	Green house gas
GRI	Global Reporting Initiative
GTK	Geological Survey of Finland
IIED	International Institute for Environment and Development
ISO	International Standardisation Organisation
LCA	Life cycle assessment
LCI	Life cycle inventory
M&M	Mining and mineral processing
MAX	Maximum scenario
MB	Mass-based allocation
MEE	Ministry of employment and the economy
MFA	Material flow analysis
MMSD	Mining, Minerals and Sustainable Development
NGO	Non-governmental organisation
NMB	Normalised mass-based allocation
PPI	Policy potential index
SETAC	Society of Environmental Toxicology and Chemistry
SLO	Social licence to operate
UN	United Nations
USGS	United States Geological Survey
VB	Value-based allocation
WGI	Worldwide Governance Indicators

List of original publications

This thesis is based on the following publications:

I Tuusjärvi, M., Vuori, S. ja Mäenpää, I. 2012. Metal Mining and Environmental Assessments - A new approach to allocation. Journal of Industrial Ecology, 16 (5), p.735-747.

II Vuori, S., Aatos, S. and Tuusjärvi, M. 2011. Geological resource accounting and associated research. In: Nenonen, K., and Nurmi, P. (eds.) Geoscience for Society 125th Anniversary Volume. Geological Survey of Finland, Special Paper 49.

III Tuusjärvi, M. 2013. Tracking changes in the global impacts of metal concentrate acquisition for the metals industry in Finland.
Resources, Conservation and Recycling 76:12–20.

IV Tuusjärvi, M., Mäenpää, I., Vuori, S., Eilu, P., Kihlman, S. and Koskela, S. The metal mining industry in Finland: Development scenarios to 2030. Submitted to Journal of Cleaner Production.

The publications are referred to in the text by their roman numerals.

M. Tuusjärvi's (M.T) contribution to the original publications was following:

I M.T. had the main responsibility for data collection, management and analysis, as well as developing the new allocation method (NMB allocation) in co-operation with S. Vuori and I. Mäenpää. M.T. made the comparisons between allocation methods, and all authors interpreted the results together. M.T. and S. Vuori wrote the manuscript with comments from I. Mäenpää, and M.T. completed the editing after receiving comments from the reviewers. M.T. was also responsible for editing the figures and tables.

II S. Vuori, S. Aatos and M.T. wrote the paper together, with S. Vuori being responsible for editing. M.T. was responsible for writing the section entitled "Life cycles and material flows".

III M.T. held sole responsibility over the data collection, management, analysis and interpretation presented in this paper, as well as writing and editing the manuscript, and preparing the figures and tables.

IV M.T. had the main responsibility for data collection and management. Construction of the model and scenarios and analysis of the results were carried out in collaboration between M.T., I. Mäenpää, S. Vuori and P. Eilu. Interpretation was carried out by M.T., who also wrote the manuscript and edited the figures and tables with comments from the other authors.

“Buy it, use it, break it, fix it,
Trash it, change it, mail - upgrade it”

Daft punk - Technologic

1 Introduction

Since the beginning of the 1970s, there has been growing global interest in environmental effects caused by human actions, and the capacity of Earth to sustain the growing human population and increasing wealth. From this interest has grown the concept of "sustainability", which can be held as the idea of a balance between the functionality of human societies and the bearable pressure they place on the natural environment and Earth resources. Sustainable development, commonly divided on confluent sections of environment, social and economic, is a process under which this balance is sought.

In contrast, the demand for mineral-based raw materials has grown faster than ever since the beginning of the 21st century, especially in Asia (Prior et al. 2013), and the generally open mineral markets have led to increased trans-continental trade flows of these commodities. Although the current economic instability that started in 2008 has lately smoothed the growth curves in base metals and iron, the growing international demand for minerals is expected to be maintained (Access Economics, 2008; Steger and Bleischwitz 2011).

The roots of sustainability are deep. Maintaining a continuous firewood supply for Saxonian silver mines in the 18th century, evoked by Hans Carl von Carlowitz, is held as one of the first sustainable development acts (Klöppfer 2003). The idea was simply not to harvest trees faster than they grow, and in this way to secure a sustainable supply of fuel for ore processing.

In modern times, the energy crisis in the early 1970s was the first impetus that led to the formulation of the philosophy of sustainability and the methodology for assessing the raw materials and energy use of production systems (Hunt and Franklin 1996). At that time, the book "Limits to Growth" by the Club of Rome (Meadows et al. 1972) was published, and the first attempt to take a systems approach to evaluate resource and energy use and the related emissions of production chains was made by the Coca-Cola Company (Franklin 1995). In the 1970s and 1980s, the methodology evolved in the U.S. and Europe (Hunt and Franklin 1996; Boustead 1996), and the term "life cycle analysis", later to be denoted as life cycle assessment (LCA), was adopted in 1990 in an open workshop organized by the Society of Environmental Toxicology and Chemistry (SETAC). A few years earlier, the Bruntlandt report had been published, including a commonly quoted definition of sustainable development: *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED 1987, p. 27).

During the 1990s and the beginning of the 21st century, the LCA methodology evolved and became a mainstream tool for assessing the environmental performance of production chains (see e.g. Guinee 2002; Feifel et al. 2010; Franklin 1995; Ekval 2005; Finnveden and Moberg 2005; ISO 2006). At the same time, sustainable development goals in industrial actions and legislation have gained ever-increasing importance, and environmental protection and social and cultural well-being have gained momentum in international development agendas, for example Agenda 21 (UN 1992).

In the minerals sector, the first comprehensive study of sustainable development issues was conducted by the MMSD committee at the beginning of the 21st century. The main report, "Breaking New Ground", was published in 2002 by IIED. Additionally, several case studies were published from different continents, including Australia, South America, North America and Southern Africa (e.g. Sheehy and Dickie 2002;

McDonald 2002; Cawood et al. 2001). In 2012, IIED published a discussion paper on the progress in the mining industry's contribution to sustainable development during the previous decade (IIED 2012). One of the most determined actions to increase the transparency of the mining industry and governance actions has been the Extractive Industries Transparency Initiative (EITI), which is a framework and guide for companies, governments and civil society for reporting the revenues collected from natural resource use and the paid taxes and funds (EITI 2013). EITI is a door opening for increased transparency in the sector in global terms, and will possibly strengthen the acceptability and social contribution of the mining industry in the long term.

Europe was not included as a case study region in the IIED (2002) report, and Norway is currently the only European country reporting according to EITI. This possibly reflects the minor role of the mining industry in the region during the two past decades. However, exploration and mining activities as well as the political importance of mining in Europe have recently increased (EU 2008: Tiess 2010). Many European countries, including Finland, are heavily dependent on imported metallic raw materials, and the increased interest in raw material issues reflects intensified competition in the global markets (EU 2008, 2010; Finland's Minerals Strategy 2010) driven by the increased international demand for bulk industrial metals (e.g. iron, nickel, and copper), high-tech metals (e.g. rare earth elements, cobalt, and lithium) and investment metals (e.g. gold).

Supply–demand imbalance and speculation in mineral futures led to strong growth in metal prices during the beginning of the 21st century and also encouraged exploration and mining investments in Europe. For the European Union (EU), the intensified competition poses a supply risk for metallic raw materials, potentially affecting the functionality of the European metal and manufacturing industry (EU 2008, 2010). To reduce this risk, political pressure has been placed on increasing the domestic supply of raw materials by mining the geological resources, but also by efficient recycling of the resources in the anthropogenic stock.

1.1 Mining: initiator of the life cycles of products

Mining represents the first stage in the production chain of metal containing products. In the modern world, these production chains can be truly global in the sense that every single production stage can practically be located in a different country or even continent. This fragmentation of production processes creates complex production systems across the globe (Van Veen-Groot and Nijkamp 1999). In open markets, the material flows of trade are controlled by location, prices and contracts. Demand develops in certain areas according to human needs for increased well-being, as argued earlier by Crowson (2008) and Steger and Bleischwitz (2011), and it appears in the forms of infrastructure and basic welfare, energy, communication and luxury.

In particular, the decreased cost and time scales of transportation and telecommunications (Radetzki 2008, Crowson 2009) have enabled increased transportation distances of minerals. Currently, global sea transportation of mineral commodities is common practice (Radetzki 2008), as well as the exploitation of mineral deposits in remote areas. To gain a coherent picture of the environmental, economic and social impacts of raw materials acquisition for an import-dependent country such as Finland, there is a need to consider the impacts of mining on the environment and society in multiple countries and several continents and, as Cadarso et al.

(2010), Van Veen-Groot and Nijkamp (1999), and Endresen (2003) have also pointed out, on the oceanic ecosystem.

The urge towards more sustainable societies has raised a need to examine how production systems work and where the negative effects of their "hotspots", i.e. weak links in the production chains, could be reduced. From this need have arisen methodologies such as LCA, material flow analysis (MFA) and numerous indicators by which sustainable development can be measured (Finnveden and Moberg 2005).

To estimate the environmental pressures of the production chains, LCA is nowadays one of the most comprehensive methods (e.g. Ekvall 2005; Guinee et al. 2002; ISO 2006). With LCA, the potential direct and indirect environmental impacts of a product or production chain could be estimated during its whole or partial life cycle (ISO 2006). In LCA studies, however, the description of the processes used in mining and minerals processing is often superficial (Awuah-Offei and Adekpedjou 2011). Also, the data concerning mining can be generic and inadequate, and cannot be used as an accurate account of the spatial and temporal environmental burdens at a same level as for downstream systems such as metals, building, chemical or food industries (Durucan et al. 2006). In addition, the increased globalization of the production systems has set another challenge for LCA methodology, demanding great detail.

Despite the reduced applicability, LCA studies on metal processing chains, including mining, have been performed, for example, by Norgate and Haque (2012), Adachi and Mogi (2007), Awuah-Offei et al. (2008), Bovea et al. (2007), Durucan et al. (2006), Mangena and Brent (2006), Spitzley and Tolle (2004) and Suppen et al. (2006). In addition, Yellishetty et al. (2009) reviewed the critical issues in applying LCA to mining, focusing especially on land-use issues. According to *ibid*., the other methodological issues in applying LCA to mining lie, for example, in abiotic resource depletion, allocation in open-loop recycling and co-production, and taking into account spatial and temporal dimensions.

1.2 Role of the mining industry in sustainable development

Mining presents a contradiction in the sustainable development context in the sense that through mining, humanity utilizes unrenewable mineral resources, which may thus not be available for future generations in their original form. Therefore, only weak sustainability (Cabeza Gutés 1996) could be supported by mining, as the natural capital is lessening on behalf of human capital (Waye et al. 2009; Mutti et al. 2012; Prno and Slocombe 2012). However, mining is currently fundamental to maintaining the societal structures in their modern form and to supporting increased well-being, and the crucial issue is to improve the environmental, social and economic sustainability of mining practises (IIED 2002).

Generally, mining has an effect on the local and national economy through royalties and other types of taxes (Brewer 2005; Crowson 2009; Waye et al. 2009), investments and employment (Törmä and Reini 2009). Economic well-being is also supported through the linkages between mining and other sectors, such as equipment suppliers, downstream processing and service sectors (Crowson 2009).

Economic effects of mining occur at national, regional, local and company levels, but the direct pressures on the environment and societies occur at the local level. Mining areas can be very large, especially in open pit mining, restricting or hindering other forms of land use. Large volumes of water are also needed for mineral processing, and the surrounding ecosystems and human societies can suffer from dust and noise if not properly controlled (see e.g. Aswathanaryana, 2003; Craig et al., 2010; Kessler, 1994). The energy usage and related green house gas (GHG) emissions may have an effect on the climate, and acid mine drainage (AMD) combined with heavy metal leakage forms a long-term risk for water ecosystems (Akcil and Koldas, 2005). However, the intensity of environmental degradation is always site specific, and dependent on the mining and processing methods, ore characteristics, the quality of environmental management and risk control, and the ability of the local ecosystem to buffer the impacts (Kauppila et al. 2011).

In social terms, the positive aspects of mining encompass the well-being of personnel and the local community in which mining is performed, as well as the increased employment levels in the region. The negative social effects may impact on competing sectors (e.g. tourism and reindeer farming), and include transfers of workforce from other sectors, indigenous peoples' disempowerment (Corando and Fallon, 2010), degradation of the quality of the local environment, and feelings of insecurity, fear and distrust in the local population (Ziessler et al. 2013; Ziessler-Korppi 2013). As with environmental effects, social effects are also always site specific. Local communities may welcome the increased employment and economic wealth, but tensions usually develop between them, national governments and mining companies as a result of contradicting views on the intensity of benefits and drawbacks of mining (Crowson 2009).

As a result, mining is at a crossroads of two sustainable development challenges: 1) the short- and long-term depletion of usable mineral resources, and 2) sustainable industrial practises, focused here on mine sites. These both reflect the different needs of human societies and individuals concerning resources, a clean environment, compensation, continuation and knowledge (Table 1).

Living in constructed, urban environments with a high level of technology creates *a need for mineral resources* (IIED 2002), reflecting the standards of living, the choices and values of individuals, and the technology used. In addition, constructed environments also serve as a supply for secondary resources via recycling and reuse, thus creating an urban (a.k.a. anthropogenic) stock of metals and minerals. Any additional resources needed after the utilization of the urban stock have to be provided by mining. Thus, mining serves as the beginning of the production chains that satisfy the material needs of society.

At the same time, the *needs for a clean*

Table 1 Society needs as drivers for the mining industry's project management style linked to sustainable development challenges

Need for	Driver to	Sustainable development challenge
Recources	Industry existence; Legislation; Research & Development	Depletion of mineral resources
Clean environment; Compensation; Continuation; Knowledge	Social responsibility; Environmental protection; Economic feasibility; Legislation; Research & Development	Sustainable industrial (here mining) practices

environment, compensation, continuation and knowledge affect the regulation of mining activities, as well as the actions of the mining industry in relation to social responsibility, environmental protection and economic feasibility. Hence, the mining industry operates under three types of pressure directed from society: 1) the demand for raw materials generated through markets via price development, 2) legislation over the style of operations, and 3) the demands of civil society for environmental and social well-being.

1.2.1 Depletion of mineral resources

The short- and long-term depletion of mineral resources is related to *the need for resources* (Table 1). This need forms a driver for the mining industry to exist, and also a driver for legislation concerning mining claims and rights to establish mining in certain regions. The need for resources combined with free trade also drives the global supply chains of commodities and goods, and the development of more efficient technologies for mining and mineral processing.

Short-term depletion is vulnerable to market disruptions, for example problems in delivery from trade partners. Imbalance in demand and supply dynamics can also lead to a short-term shortage of raw materials (Crowson 2008). Long-term depletion is an ultimate type of depletion, where the usable resource of a raw material is expected to come to an end at the global level. Multiple studies have been conducted to estimate the time spans for the adequacy of known resources (e.g. Lee 1998; Maggio and Cacciola 2012; Mason et al. 2011; Yaksic and Tilton 2009). However, in the case of many raw materials, substantial growth has occurred in both cumulative production and the quantity of resources over time (Mudd et al. 2013), and Tilton and Lagos (2007) argue that markets will ultimately correct the problem of resource depletion though increased prices, replacing raw materials and developing technologies.

The quality of mined reserves has deteriorated over time (Mudd 2010, 2007), which has been seen as a consequence of the depletion of the best high-grade deposits (West 2011). However, the high metal prices during the first decade of the 21st century have also *enabled* the utilization of poorer deposits (Hinde 2012), and the developments in metallurgical technologies, movement towards high-volume and lower cost extraction technologies, and advantages of extending the mine life over establishing new mines are other reasons for the declining ore quality (West 2011, Mudd et al. 2013). However, as the utilized deposits become poorer, the environmental and social costs of their utilization may increase and ultimately restrict the full utilization of these resources in the end (Ernst 2009; Mudd 2010; Giurco and Cooper 2012; Mason et al. 2011; Prior et al. 2013).

1.2.2 Sustainable mining practises

Sustainable mining practices reflect the *needs for a clean environment, compensation, continuation and knowledge* (Table 1). Fulfilling these needs provides the main drivers for social responsibility and environmental protection by which companies work to gain their social license to operate (SLO), which is held as a derivative of the local stakeholders' approval or acceptance of the mining activity (Prno and Slocombe 2012). In addition to company behaviour, the mentioned needs also drive legislation set by governments.

Environmentally friendly and socially feasible mining practises have not always been in the focus of the mining industry, and the legacy of past carelessness has a strong effect on the opinions towards mining today (IIED 2002). Mirroring this configuration, the industry has to perform well in both environmental and social issues to convince the general public of its actions.

The industry is responsible for sustainable mining practices, which includes social responsibility, environmental protection and profitability (Figure 1). Social responsibility is usually tightly bound to corporate social responsibility (CSR) strategies, which in the case of the mining industry generally include performance reporting and programmes to increase employee well-being and safety. In addition, various ways to increase the well-being of local communities include, for example, investments in schooling and infrastructure, as well as funding and/or taking part in societal activities.

In addition to fulfilling a set legal frame, many companies practice their social responsibility at a higher level to earn their SLO (Eerola 2013). However, the most important objective for a private company is to make a profit, as this secures the continuation of the company's operations (Crowson 2008). The critical issue for mining companies is then to manage and fund their operations so that all these aspects of sustainability are covered at a balanced level.

1.2.3 Importance of the societal context

Economic, social and environmental benefits and drawbacks of mining rely heavily on the societal context in which it is practised. The quality of governance, activity and freedom of speech of civil society and the ability of mining companies to establish and realise environmental protection and social prosperity define the

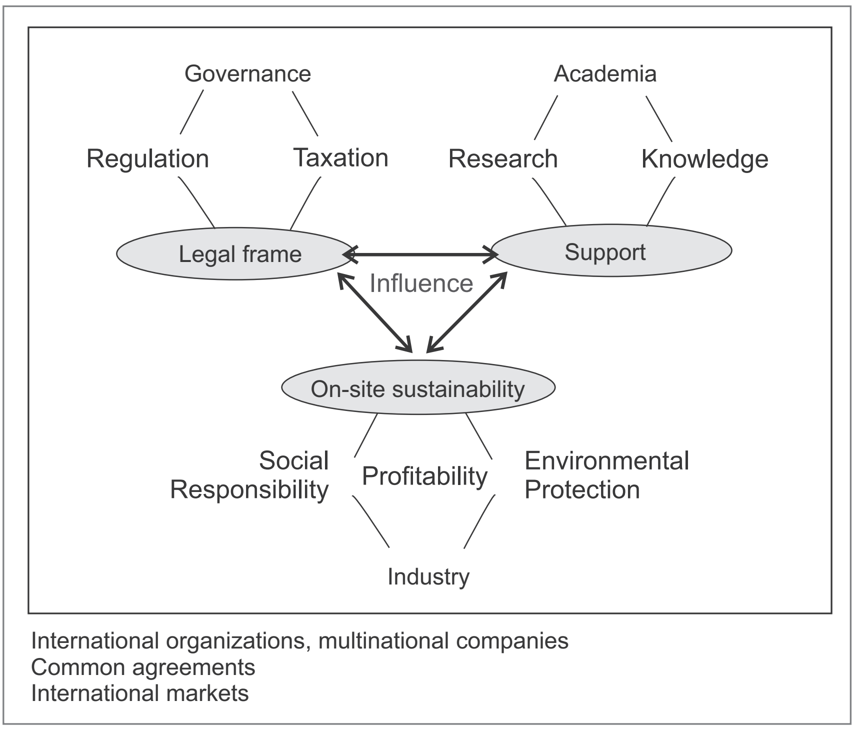

Figure 1. General roles of governance (national, regional and local decision making), academia (universities and research organisations) and industry in promoting an economically, environmentally and socially feasible mining industry

societal context. Governance, academia and industry are the key actors defining the context for sustainable development in mineral resource use, and the functionality of all these actors and co-operation between them are a necessity for an economically, environmentally and socially feasible mining industry (Figure 1). Prno and Slocombe (2012, and references therein) and Eckerberg and Joas (2004) have argued that the governance in many countries has lately widened both vertically and horizontally as the role of civil society, transnational actors and non-governmental organizations has increased alongside traditional governments. This reflects the overall change that is advancing in the governing of mineral resources. For clarity, the term "governance" in this research refers, however, to the traditional governing executed by national, regional and local decision makers.

In advancing sustainable development in the mining industry, a general role of governance is to create a legal framework under which mining is practised (Waye et al. 2009; Kraufmann et al. 2010). The role of academia is to support decision making by providing scientific information (Klöpffer 2003), and the role of the industry is to accomplish sustainability in its operations (IIED 2002) as discussed in the previous section. From the mining industry's viewpoint, the most important roles of governance are to stabilise the legal framework under which mining companies operate, and to help to maintain investors' interest in securing the continuation of mining. Security of tenure, stability of the terms of regulations, and the ability to repatriate profits have been stated as the most important factors supporting mining investment (Waye et al. 2009; Otto 2005; Pritchard 2005; Williams 2005).

Environmental protection and socio-economic benefits can be promoted by governance via two direct routes: 1) by setting and maintaining adequate minimum requirements for the industry's performance in environmental protection and social responsibility, and 2) by transforming mineral capital to social capital via taxation (Waye et al. 2009). According to *ibid*., the most common forms of taxation are *unit-based royalties* based on unit volume or unit weight, and *ad valorem royalties* based on a mineral's value. Tax based on profit or income is a subtype of *ad valorem royalty*, as is a gross income royalty based on the value of production, which could be based on different definitions of the production value. According to Waye et al. (2009), gross royalty appears to be the most beneficial to society, but also a significant risk to the industry, possibly stifling investment. In contrast, profit-based royalty is generally preferred by the mining industry, but the value to society may prove small at times of low profit, and in exploration and mine construction phases of the mine life cycle. The contradiction between striving for investment and collecting tax returns renders the formulation of mining taxation challenging (Waye et al. 2009).

In supporting governance and industrial activities, academia (i.e. universities and research organisations) has a crucial role as the provider of scientific support through research and knowledge. The ultimate role of academia in promoting sustainability of the mining industry is then to provide independent, holistic and systematic knowledge on mineral resources and the economic, environmental and social effects related to their use, as well as taking part in developing efficient and environmentally sound technologies.

In addition to the national, regional and local legal and civil society contexts, mining industry practices are strongly influenced by international agreements and practices. Possibly the best example of these are codes for the reporting of exploration results, mineral resources and ore reserves, which set minimum standards for public reporting on these issues (e.g. CRIRSCO family codes; see Henley 2013). The internationally agreed coding ensures the reliability and transparency of prospecting results, and following these is generally the only way to obtain exploration and mining investment. Lately, another type of international reporting has gained importance, one example being the Global Reporting Initiative (GRI), which promotes globally applicable and voluntary sustainability reporting guidelines. Under the GRI reporting family, the mining industry has its own reporting framework (GRI 2010).

1.3 The metal mining industry in Finland

Increased price levels of metals have recently resulted in intensified mineral exploration and mining in Europe, and especially in the Northern European countries Finland and Sweden. These countries have a long history of mining starting from the 16th century and continuing in Finland until the end of the 1980s (Puustinen 2003), and in Sweden until today. In Finland, the metal mining industry suffered a downturn in the 1990s, which reversed a fast-growing boom at the beginning of the 21st century (PwC 2012), reflecting a similar trend also noted in other countries (Prior et al. 2013). The boom attracted several domestic and foreign exploration and mining companies, and several new metal mines were opened in the early 2010s. In addition, the mining law in the country was renewed (Mining Act 621/2011), with increased attention being paid to environmental and societal aspects of mining and increased compensation to property owners.

New activity is especially focused on base metals and gold, but deposits of platinum-group metals and iron are also being explored. The interest in mineral resources in Finland is also reflected by the highest rank in the Fraser Institute's 2012/2013 survey for mining companies (Wilson et al. 2013). The new activity has increased expectations towards the mining industry to provide a new economic stimulus, especially in the economically regressive areas of Eastern and Northern Finland (Hernesniemi et al. 2011; Törmä et al. 2013; Törmä and Reini 2009), and possibly provide a boost to the national economy (Finland's Minerals Strategy 2010; Hernesniemi et al. 2011; Reini et al. 2011). However, concerns over a sufficient balance being achieved between regional socio-economic benefits and environmental impacts have recently been expressed by several authors (e.g. Eerola 2008; Haltia et al. 2012; Rytteri 2012), as well as by the general public. Although many of the mining companies are performing well in their environmental protection (e.g. HS 2012; Inmet Mining 2012; YLE 2013), the continuous environmental problems at one of the largest new mining operations (Talvivaara 2013; Talvivaara 2012a; Talvivaara 2012b; Talvivaara 2012c; Talvivaara 2010) have had a negative impact on public trust regarding the viability of the mining industry in the country (Rytteri 2012).

In the wet and cold boreal climate of Finland, the most important local environmental pressures are related to water and the potential to generate AMD and release heavy metals (Kauppila et al. 2011). The public economic benefits of mining are generated through profit taxation, being 24.5% in 2013 and divided between national and local government, as well as progressive income taxation, and investments in construction generating real estate taxation (Törmä et al. 2013; Törmä and Reini 2009). Landowners benefit from annual compensation based on the used area and value of mining products (Mining Act 621/2011). The minerals industry, construction industry and metals industry, in particular, have already benefited from the new mining activity (Törmä et al. 2013).

Under favourable economic and political conditions, the growth of the mining industry in Finland is expected to continue in the coming years. This raises a question of how the potential negative environmental and social consequences could be mitigated and positive aspects emphasized to maintain the industry's SLO. Recent discussion in Finland concerning the social effects of mining has culminated around this subject (Eerola 2013, 2008; Jartti et al. 2012; Mononen 2012; Rytteri 2012; Sairinen 2011; Ziessler et al. 2013; Ziessler-Korppi 2013), The rapid increase in mining and exploration activities, recent environmental problems and the "rush" of foreign mining companies to the country have prompted fears and opposition towards mining and mineral exploration (Eerola 2013; Ziessler et al. 2013; Ziessler-Korppi 2013), and it is evident that renewing and maintaining the SLO at both local and national levels is fundamental to the long-term prosperity of the industry in the country.

1.4 Aims of the thesis

Reflecting the issues discussed in the introduction, the present thesis research focused on five questions:

i) In terms of LCA and MFA methodology, what would be the most viable way to allocate the physical inputs and outputs of the mining and mineral processing operations between the products?

ii) What is the role of governmental research organizations in supporting sustainable development in the minerals sector?

iii) What are the domestic and international environmental effects related to mining and mineral processing in the supply chain of metals?

iv) Can one make predictions on the development of the metal mining industry in Finland in the coming decades? What are the potential effects on environmental and socio-economic performance?

v) How can the benefits and drawbacks of the Finnish mining sector be balanced in a sustainable way in the future?

2 Review of the original publications

2.1 Paper I: Allocation methodologies in life-cycle studies

In the study reported in this paper, the application of methodologies such as LCA and MFA in metals mining was studied, especially in the context of input–output allocation in the inventory phase. The paper presents a methodological extension for allocation when applied to mining, together with case studies on four mines.

The majority of the metal mines produce multiple metals as products. Therefore, this 'multifunctionality' of the mining process should be solved by allocation in the inventory phase. Allocation refers here to the partitioning of system inputs (e.g. raw materials and energy) and outputs (e.g. waste materials and emissions) between the products. Although the methodology of LCA is standardized, the methodology for solving the multifunctionality problem by allocation has remained controversial.

The ISO standard for LCA (ISO 2006) sets general conditions for solving multifunctionality in product systems. The most favourable option according to this standard is to avoid allocation, i.e., dividing the inputs and output of the system between its co-products. The avoidance of allocation has been studied by Weidema (2000) and Weidema and Schmidt (2010), and this methodology is argued to be best suited to prospective LCA studies. For account-oriented LCA studies, the use of allocation methods based on physical or monetary characteristics of products is a generally applied option.

In this paper, we consider the applicability of different allocation methods in mining-related life cycle inventories (LCI). The paper includes an introduction to a new normalized mass-based (NMB) allocation method, and comparisons between the NMB allocation method and the two prevailing methods (mass-based (MB) allocation and value-based (VB) allocation). The paper also includes case studies on the application of the studied allocation methods in the estimation of the CO_{2eq} emission factors for four mines.

The new NMB allocation method is based on the MB allocation method. In the NMB method, the masses of mined metals are normalized to the crustal abundance of the metals. The use of crustal abundance as a reference is supported by the dependency between element abundance in the upper crust, metal prices and average ore grades in metal mining. This removes the need for additional price data to be used in allocation in describing the economic importance of products.

The defined NMB allocation method offers a reasonable alternative to MB and VB allocation methods in the case of metal mining. The new method reflects changes in production while taking into account the varied economic importance of produced metals. The main disadvantage of the MB allocation method is the inability to reflect the economic importance of mined metals. In VB allocation this problem is solved, although fluctuations in allocation not dependent on physical changes in production can occur.

The selection between allocation methods does not necessarily generate notable differences in derived CO_{2eq} emission factors (e.g. for zinc). The crucial aspect is the difference in ore grades between produced metals, e.g., combined mining of zinc and silver can potentially cause differences in allocation results. Generally, for valuable metals mined at especially low ore grades (e.g., gold, silver, palladium, platinum and rhodium), the differences can be significant. This emphasizes the increased importance of uncertainty and sensitivity analyses when the unit prices rise.

2.2 Paper II: Role of geological surveys in supporting the sustainable use of resources

In the study reported in this paper, we considered the role of governmental research institutions in promoting and supporting sustainable resource management at the national level. The Geological Survey of Finland (GTK) served as a case example.

The paper recognizes that geological resources have an essential role in supporting the functionality of a modern society. Furthermore, the increased global need for these resources emphasizes the efficient location and quality based management of these resources. In Finland, this information has traditionally been separated under the control of different governmental research institutions and authorities.

In the course of developing novel “accounting concepts”, this information is merged to provide knowledge on the availability of mineral resources (and other geological resources such as peat, groundwater and secondary resources) at the national level. By also including information on the location, the accounting concepts serve as (web-based) support for land-use planning in resource-rich areas. In addition, in the areas of primary resource deficiency, accounting can support the management of secondary resources.

The accounting concept for aggregate use is used as an example in the paper. In this case, the co-operation between national and local government, industry, and governmental research institutions was needed to establish a web-based accounting service. The publicly open service contains information on the location, use and reserves, combined with information on geography as well as natural conservation and groundwater areas. This is a good example of the value-added services generated by successful collaboration between different actors and the combination of various knowledge bases.

In addition to data collection and management, governmental research institutions also take part in basic and applied research activities, being a part of academia. In the case of GTK, current research is divided into the fields of mineral resources and mining, mineral processing technology, environmental impact prevention, and land-use and social issues related to the use of mineral resources. Research related to the sustainable use of resources places special emphasis on strengthening the use of secondary waste mineral resources, and assessing the environmental effects of mining-related material flows in terms of LCA and MFA methodologies. Through efficient and aggregated data management and applied research, the geological surveys support the government in managing the mineral resources use, and take part in research enhancing the technological, social and economic performance of the mining and mineral processing sectors.

2.3 Paper III: Changing environmental impacts on the international supply chains of metals

The metals industry in Finland is heavily dependent on imported mineral concentrates, and this paper considers the environmental impacts of the international supply chain of mineral raw materials related to the Finnish metals industry. The governance framework in the producing countries is also examined. The paper concentrates on iron, zinc, copper and nickel concentrates, and the change in the impacts between 2000 and 2010.

The examined indicators for material flows and climate impacts include: 1) mineral concentrate flows, 2) waste minerals, 3) CO_{2eq} in mining and mineral processing, and 4) CO_{2eq} in transportation. To consider the quality of governance in the supplying countries, the following indicators were used: 1) Worldwide Governance Indicators (WGI) (Kraufmann et al. 2010), 2) the Corruption Perception Index (CPI) (Transparency International 2010), 3) the Environmental Performance Index (EPI) (Emerson et al. 2010), and 4) the Policy Potential Index (PPI) (McMahon and Cervantes, 2011). The WGI represents a set of indicators describing the various aspects of governance. For this paper, the WG indicators selected were ‘Voice and Accountability’, ‘Regulatory Quality’ and ‘Rule of Law’. CPI describes the amount of corruption occurring in the public sector, and EPI describes how far the countries are from established environmental policy goals at the national governance scale. PPI describes the interest of mining and exploration companies in investing in different countries and reflects the potential to find new mineral resources, but also the transparency and predictability of local governance, as well as the political conditions in relation to mining entrepreneurship.

The results indicate markedly higher environmental effects abroad in comparison to the impacts in Finland. This is based on the high dependency of the Finnish metals sector on imported raw materials. However, the overall environmental pressure decreased from 2000 to 2010 due to the decreased need for primary resources, but also due to the increased share of underground mining. Differences between source countries were detected to be large, and changes in the distribution of source countries can therefore have a marked effect on the mining and mineral processing related environmental burdens in the supply chain of metals. However, uncertainty is added to the results by the lack of a comprehensive dissection of mine-specific energy use and the CO_{2eq} emission levels, and by uncertainty related to the input–output allocation, especially in the supply chains of copper and nickel. The ore grade, mine type (open-pit or underground) and the national electricity mix appeared to be the most important factors behind changes, but the sea transportation distance also had a relatively large effect.

The largest environmental pressure was related to copper concentrates, which also had the weakest performance in governance quality. For iron, zinc and copper, there was an increasing trend in the ability of governments to formulate and implement sound policies and regulations, their compliance in society, freedom of expression, and the general willingness to invest in mining and mineral exploration. For these metals, the corruption in governance decreased. However, the quality of governance related to nickel concentrates weakened.

Future changes in the supply chains of primary raw materials for the Finnish metals industry in environmental terms will most likely relate to developments in nickel and copper concentrate acquisition. The waste mineral amounts and CO_{2eq} emissions related to copper cover the largest share of the total burden, and thus changes in the source countries may have an effect on the total environmental pressure. For nickel concentrates, the increasing proportion of domestic mining will most probably increase the environmental pressure of the supply chain, although the governance quality might improve.

2.4 Paper IV: Future development of the Finnish mining industry

In the study presented in this paper, the possible future development of the metal mining industry in Finland was assessed by constructing three scenarios presenting possible developments of the industry in terms of material flows and economic and environmental performance. The scenarios included: 1) the best-estimate (BE) scenario, 2), the base-level (BL) scenario, and 3) the maximum (MAX) scenario. The BE scenario describes the probable evolution of the Finnish metal mining industry in a continuous positive market situation for mining. The BL scenario describes the situation where no new mines are opened, and the MAX scenario describes the development where all planned new mining operations and extensions in the existing mines will occur. The MAX scenario also includes some of the current exploration targets, which increases the uncertainty in the results.

The BE and MAX scenarios show continuous growth in the industry in the coming years especially in terms of the value of production, waste minerals and indirect CO_{2eq} emissions. This reflects the situation where the profitability outlook of the mining projects and prospects is positive or very positive, respectively. In BL scenario, there is a small growth in value of production and waste minerals but otherwise the indicators in this scenario are declining. The strongest decrease is observed for direct employment and ore mining.

According to the results, the metal mining industry seems to have a good potential to bring positive socio-economic development, especially to the economically regressive northern and eastern parts of Finland. The metal industry and the mining equipment industry potentially also benefit from increased mining activity at the national level (Reini et al. 2011; MEE 2013). Alongside the potential economic benefits, however, the increased potential for environmental degradation hinders the otherwise good development.

According to the results, the amount of waste minerals is expected to significantly increase, especially in the BE and MAX scenarios. This may reflect an increased potential for AMD if the mined waste rock and tailings contain acid-generating minerals. The potential is not necessarily proportional to the amount of waste rock, based on the decreasing ore grades and more efficient mineral processing technologies. However, the deposition of large masses of unused rocks and minerals requires land, especially in open-pit mining, and may thus intensify local land-use-related conflicts.

The results suggest that the CO_{2eq} emissions related to mining, minerals processing and other downstream processing at the mine sites will increase in the future, although in comparison to the national level (Lehtilä et al. 2012) the emission levels will remain moderate. A national decrease in the CO_{2eq} intensity of electricity production and increased energy efficiency at mine sites would help to reduce the CO_{2eq} emissions of mining.

The metal mining industry seems to have a good potential for benefiting Finland, especially the economically regressive northern and eastern areas. However, a balance between local socio-economic benefits and environmental degradation is needed in the future to maintain the industry's social license to operate in the long term.

3 Discussion

In this thesis, the research topics range from a detailed methodological study on applying LCA and other assessment methods to mining (paper I) to the role of governmental research institutions in supporting the sustainability of mineral resource use (paper II), the environmental pressures of mineral-based trade and global production chains (paper III) and the development scenarios of metal mining in Finland, with discussion of the potential environmental and socio-economic effects related to the assessed scenarios (paper IV).

3.1 Reaching towards a sustainable mining industry in Finland: A framework of influence

Figure 2 illustrates the influence of governance, industry and academia on mining practices in the dimensions of *practice* vs. *theory*, and *local* vs. *global*, reflecting the situation in Finland. Additionally, the keywords *sustainable mining practices, governmental research institutions, methodological development,* and *sustainable production chains*, reflecting the studied topics, are placed in the same context. The idea of this framework is to clarify the role of different actors influencing the mining industry's practices and the societal context in which mining is performed. At the same time, the framework emphasizes the importance of the co-operation between these actors, which was already illustrated in Figure 1.

The mining industry has a strong practical role as an initiator of mineral exploration and mining. The field of the *mining industry* in Figure 2 reaches from the *local* to the *global* dimension, reflecting the strong local emphasis of practical actions, combined with the strong connection to

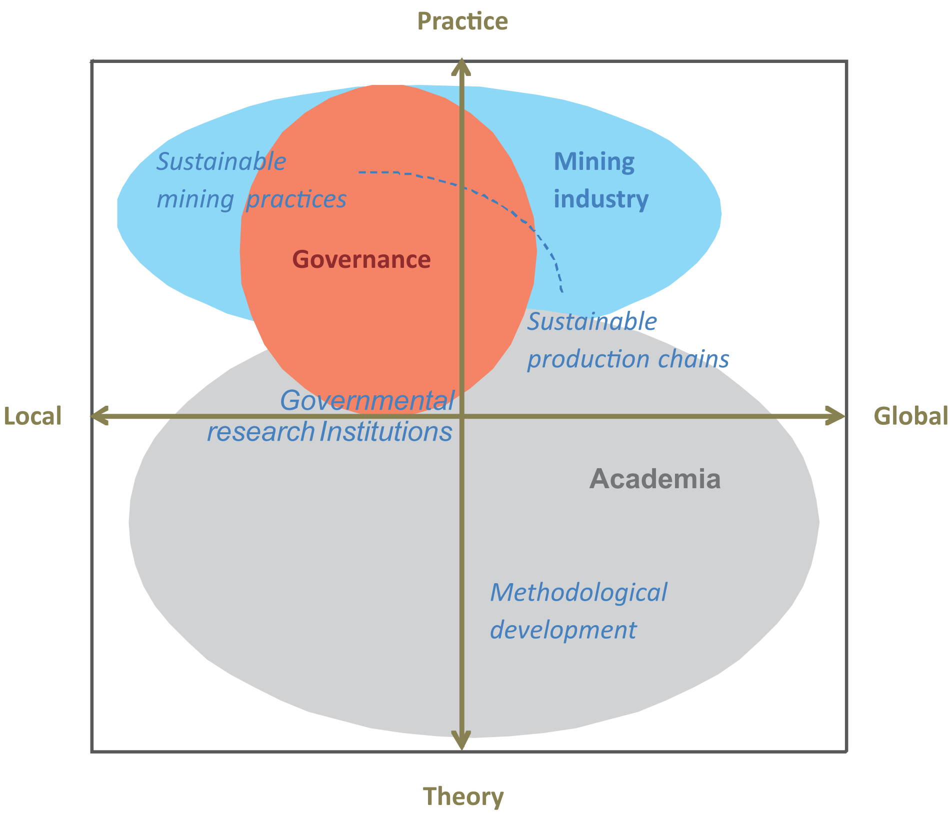

Figure 2. A framework of influence in reaching towards sustainable mining practices in Finland. The figure describes the influence of fields of governance (orange), the mining industry (blue) and academia (grey) in the dimensions of practice vs. theory and local vs. global, with keywords reflecting the dissected research topics

the international minerals market, international codes of practise, and the multinational nature of many mining companies operating in Finland.

In contrast to the *mining industry*, *academia* has a strong affinity for the dimension of *theory*. This reflects the key role of universities in scientific research, which is characterised by a large field on the *theory* side. However, the field is also widened to the *practice* side and overlaps with the *mining industry* field, as well as the *governance* field. This reflects the co-operation of universities and research institutions with governments and other governing institutes and industry, especially in practical and applied research (paper II).

Finally, *governance* has the smallest, but most overlapping field of influence, reflecting its role in shaping the legal environment, guiding both the *mining industry* and *academia*. The influence over the *mining industry* is larger than that over *academia*, reflecting wide legislation over mining practices, for example in environmental issues, safety, mining and exploration concessions and compensations.

Of the keywords, *sustainable mining practices* is placed in the far corner of the *practice-local* sector, reflecting its practical nature and close connection to people. This keyword overlaps both *governance* and *mining industry* fields, reflecting legislation dealing with, for instance, environmental and social performance, taxation and compensation. The part not overlapping the *governance* field reflects the voluntary actions of companies to strengthen their SLO, especially in social issues and communication not directed by the law (see Eerola 2013; Ziessler-Korppi 2013). In practice, however, mining companies can perform different types of actions depending on their size, ownership structure and motivation. Exploration companies and junior mining companies, in particular, may lack the same level of resources and knowledge in implementing CSR strategies as larger and multinational companies. There might also be a lack of interest in directing resources to social responsibility actions in exploration and mine development stages, when continuation to the mining phase is not guaranteed. The company strategy might also be to exit the project before the production phase. This reflects the high uncertainties related to prospecting and the fluctuating nature of the industry. However, many authors argue that opinions and expectations towards mining are already created in the prospecting stage (Eerola 2013; Thomson and Joyce 2008; Ziessler-Korppi 2013), and in this sense the role of governance in knowledge sharing and guidance for smaller actors is emphasized.

In Finland, the government has lately taken a strong stand on supporting the sustainability of the mining industry by shaping an action plan for the "sustainable mining industry in Finland 2030" together with the industry, academia and NGOs (paper IV; MEE 2013). In addition, the government provides guidance for the actors in the field through a "mining academy" to provide support for the industry, especially in stakeholder engagement (Eerola 2013). This is an example of the "soft" way in which governance can guide and promote viable industry actions outside legislation.

The practicalities of the mining academy have been placed under the responsibility of the Geological Survey of Finland (GTK). This is an example of the triple role of *governmental research institutions* between *academia, governance* and *industry*. Firstly, the governmental research institutions perform high-level scientific research, especially in applied subjects in their fields of expertise (paper II). Secondly, these institutions provide support and expertise to the government and industry in their field. Thirdly, the institutions serve as data collectors and providers, which in the case of GTK means providing applied knowledge on the quality, location, volume and use of mineral deposits in the form of resource accounting (paper II). This provides information to the government on the availability of national resources, and the possible changes in the mineral sector associated with resource locations, quality, and abundance having an effect on potential environmental and socio-economic impacts.

The *methodological development* for considering applications specific to the mining industry in assessment methodologies such as LCA and MFA, together with research on *global production chains*, are placed in the academia field. The connection between *sustainable mining practices* and *global production chains* reflects the international nature of the production chains of metals, starting from mines.

In the case of methodology and assessments, Figure 2 could also contain the dimensions of *general* and *detailed*. For clarity, this subject is discussed in more detail in the next chapter.

3.2 Applying mining to assessments of production chains

In environmental assessments defining environmental performance and hot-spots of mining and mineral processing (M&M), three subsets, considered in this thesis, can be recognised. These are: 1) M&M as an initial stage of production chains, 2) the quality of data, and 3) a representative description of the physical inputs and outputs of M&M and their allocation between the M&M products.

Environmental effects, especially those related to energy use, are usually minor in M&M stages in comparison to the smelting and refining stages in the production chains of metals. This is most evident in the case of base metals, aluminium and iron (Adachi and Mogi 2007; Norgate et al. 2007; Schüller et al. 2008). However, if not effectively prevented, the local environmental pressures of mining can be significant in terms of waste production and water pollution (Kessler 1994). When the ore grade decreases, the potential for an environmental burden tends to increase (papers I and III). This increases the importance of mining-related environmental impacts on production chains, as a general global trend appears to be that the metal ore grades are decreasing, project sizes are increasing and processing technologies are diversifying (West 2011). This calls for more detail on the environmental pressures generated by mining than is currently achieved in many studies on the life cycle impacts of metallic products.

On a national level, at least in Finland, the data for mine sites is generally readily accessible through public reporting of the companies and the public environmental impact assessment reporting (papers III and IV). In the contrary, for international studies on production chains, the data quality and representativeness can be very heterogeneous (paper III). The situation has been improving via international databases providing information on mining. Examples of these include Raw Materials Data (IntierraRMG, 2011) and different LCA databases such as Ecoinvent, GaBi and GEMIS. For primary material flows, such as products or raw materials produced and traded, a relatively high quality data set exists, provided on the site (e.g. IntierraRMG and companies), national (e.g. governments and research organisations), regional (e.g. Eurostat and USGS) and global level (e.g. UN trade statistics).

Considering the information on hidden flows (e.g. waste minerals and tailings) or energy and substance use, the information is far more restricted, and is usually insufficient for more than general analysis at the global level (paper III). The situation is, however, changing due the industry's own actions and reporting. Many mining companies already use the Global Reporting Initiative (GRI) guidelines in their sustainability reporting, and a new business branch focused on collecting and sharing this information with third parties has also emerged (see e.g. Farrel 2009 and Eccles et al. 2010). However, although the data in LCA databases, for example, can be very detailed for specific locations, its usability for other locations may be restricted. This may generate a false feeling of security over the representativeness of the results, and emphasizes the importance of the uncertainty and sensitivity analyses, as explained by ISO (2006).

In addition to information on the physical inputs and outputs of M&M, assessments over the production chains of metallic products require meaningful allocation of these inputs and outputs between the products. This arises from the fact that multiple products (e.g. copper concentrate and zinc concentrate produced from the same mine site) are part of different downstream production chains. The problem over allocation is a long-debated issue, especially in the field of LCA, and common agreement on how it should be applied has not been reached (paper I). The application of different allocation methods in mining products was discussed in papers I and III, and the potential for allocation to create marked uncertainty in the results was highlighted. The potential seems to increase when the ore grade decreases and unit prices of metals increase (paper I). Based on paper I, it seems that when mining is considered as a part of *production chains*, allocation based on product value with average prices, or on product mass normalised with the composition of the lithosphere (NMB allocation), generates the most stable results in allocation. However, when comparing *mining in different countries* (not part of the production chains), the most representative method seems to be allocation based on product mass, reflecting the intensity of impacts per produced metal unit (paper III). This approach reflects the material and environmental efficiency with which the mined material is utilised, and thus clarifies the comparison between individual mines and countries.

In environmental assessments considering mining, a strong division between *local* and *global* aspects, and between *detailed* and *general*, seems to prevail. The opposite extremes are specific assessments of the environmental effects of mining at the local level and general assessments of environmental effects related to global production chains. However, increasing detail in data banks, especially in the terms of site-specific effects, creates a potential for narrowing this gap in the future, and also adding detail in assessments considering international production chains.

3.3 Future directions of the metal mining industry in Finland

Mined volumes have been increasing rapidly in Finland since the beginning of the 2010s, and this growth will probably continue (paper IV). The variance between development scenarios presented in paper IV is, however, wide and provide a range of possible development routes. In addition to the examined scenarios, low price levels of metals can push the development below the estimated base level if the profitability of mining weakens so that closures or suspensions of individual mines take place. This is a derivative of a common uncertainty typical for studies of the future (World Economic Forum 2010), as well as the cyclic nature of the mining industry controlled by the economic cycles, and the balance between supply and demand for mining products. However, without a severe and long-term general economic recession depressing the prices of metals, serious environmental problems, or strong legislative tightening concerning mining in Finland, the metal mining industry seems to have a good growth potential in the country. The political rationale to support the mining industry is founded on the locations in Eastern and Northern Finland of most of the already operating mines, as well as the mine development and advanced exploration projects, which are expected to support the local economic development in these formerly and currently economically regressive areas (paper IV).

A shadow over the possible good development in economic terms is created by the possible increases in mineral waste, energy use and CO_{2eq} emissions (papers III and IV). These outcomes will increase both direct and indirect pressures on the local environment and climate, materials use and land use. This may increase social pressure and discussions over the necessity to conduct mining in Finland, especially when the negative environmental and socio-economic effects are generally emphasized over positive ones in the media. Finland is already strongly dependent on imported mineral raw materials (paper III), which may lead to not-in-my-backyard (or -country) thinking, but also opposing arguments over maintaining domestic supply security and justification of outsourcing the negative side-effects of mining abroad.

Triggered by the negative environmental and social side-effects of the current mining boom in Finland, industry and government have realized the need to boost especially environmental management and technological development in mining. If these measures succeed in reducing the negative impacts, the planned actions (MEE 2013) will most probably also have a positive effect on the industry image and strengthen the SLO at local and national levels. Possible new innovations in mining, processing and environmental technologies may also strengthen the already good brand of Finnish mining and processing technology abroad.

However, success in economic and social terms is strongly dependent on the general development of metal prices, which has a direct link to the profitability of mining companies (paper IV). Especially during recessions, reductions in human and economic resources used for voluntary social responsibility actions and communication may be introduced to minimise costs. This is emphasised especially in small companies that lack support from large, and usually international, parent companies. Recessions also have an effect on profit levels, and consequently on local and national economic benefits gained via taxation. In good times, when the prices are high, companies potentially make good profits and/or investments, a share of which benefits the national, regional and local economy via employment, profit taxation and real estate taxation. During economic downturns, the profits and therefore profit-based tax receipts may be low, and drawbacks in employment and investments can occur. All this reduces the socio-economic benefits of mining during economic downturns, while the environmental pressures may prevail. Therefore, in addition to controlling environmental protection and social responsibility, to improve the sustainability of mining practices, a challenge lies in buffering the fluctuations in the mining and metals market.

Currently, Finland is considered a very interesting country to invest in exploration (Wilson et al. 2013), which reflects the stable legislative and societal context, geological potential and favourable taxation levels. However, if the socio-economic benefits do not materialise as expected, or the environmental pressures noticeably increase despite efforts to improve environmental management and technology, possible reforms of mining taxation, particularly benefitting the local communities, should be considered in the future. An interesting difference between already established mines, started prior the 1990s, and new projects is the effect of globalisation and ease of travel in the 21st century. With the current way of life, communities may lack the same level of benefits as occurred earlier, when the workforce actually lived in the neighbourhood of the mine, as the increased economic and social freedom have allowed people to choose more freely in which communities or even countries to live while working at a mine. The size of the workforce needed at mines has also continuously decreased due to technical development, and the need for a specialised education has increased, which hinders the possibilities for direct employment of local people by the mine. Guaranteeing reasonable benefits for local communities thus sets new challenges for mining companies, but also for governments in formulating mining legislation.

According to earlier studies (Waye et al. 2009; Otto 2005; Pritchard 2005; Williams 2005), stability and predictability are more important to the mining industry than precise taxation levels. However, the possible reform should be executed in a way that takes into account the high risk levels of mining investment, especially during the early stages of operations, and the cyclic nature of the industry, without placing too much pressure on profitability levels. This is needed to maintain interest in investing in exploration and mining in the country in the future, to support the continuation of the industry.

The role of international organisations, common agreements and competition over investments in the international markets will most probably continue to shape the operational and legislative environment of the mining industry in Finland. The effect of legislative development inside the EU, in particular, will most probably continue to increase. The EU will also have an increasing effect on the work of governmental research institutions and universities by strengthening the co-operation between academia and industry inside the EU via large funding programmes (see e.g. Framework 7 and Horizon 2020 funding programmes). At the same time, pressure from civil society in environmental and social terms will most probably continue to increase, and the importance of good performance at mine sites and the need for benefits to reach local communities will not diminish in the future. This calls for continued improvements in environmental and social performance at mine sites, combined with the continuous adaptation of governance, academia and industry to increasingly internationalising environment.

3.4 How sustainable is the Finnish mining industry?

The question of determining the level of sustainability of the mining industry is a complex issue, and it could be argued that complete sustainability can never be reached, as there is always room to be more sustainable. However, one way to analyse the level of sustainability is to consider i) the societal context, ii) on-site practicalities, iii) the potential for continuation of the mining activities, and iv) the status of research and development in the field. This thesis can bring some light to these aspects.

In the societal context of mining, the quality of governance and societal freedom of individuals are the defining factors in the context of sustainable development. These were considered for several countries in paper III by examining the political conditions and the freedom of civil society. In the light of this study, political maturity and the freedom of speech are at a high level in Finland compared to many resource-rich countries. In this sense, the industry (or the societal context in which it is operating) can be considered relatively sustainable. Finland has a good starting point for transparent and prosperous legislation over mining, and the freedom of speech provides a possibility for individuals to have an effect on societal activities. In this respect, the overall values of Finnish society determine, in the long term, the emphasis of legislation and common practice of mining in the country.

The environmental protection and safety has greatly increased in the mining industry from the times of Hans Carl von Carlowitz and Saxonian silver mines mentioned in the introduction. For example, the conditions in the Finnish mines have constantly improved from 1960s to recent times (Hernesniemi et al. 2011; Hakola 2009). Currently the majority of the mining companies seems to be performing relatively well in their environmental protection and safety (papers III and IV), and in this respect the industry can be claimed to follow the principles of the sustainable development. However, the subject is complex, as mining always creates pressure on the environment, and judging the acceptable or sustainable levels can be challenging. The Finnish mining industry has earlier been defined by rather small mining operations and underground mining. However, the current mining boom has changed the development towards larger open-pit operations, common in many mining countries, which partly explains the increase in the environmental and social pressure identified in papers III and IV, and increases the need for well-planned and executed environmental management. The performance in this determines the future sustainability of the industry in environmental terms.

In social terms, the new mining projects have been in focus lately, as the most significant impact a mine generates in the local communities occurs at this stage of the mine life cycle. Other marked changes occur at the closure stage, but as can be seen from the stable status of the already established mines in Finland (some of these already started operations in 1960s!), the actual production stage does not necessarily trigger conflicts between the mining company and local communities if environmental and social management is handled properly and the mine benefits the community. Working safety and income levels in the Finnish mining industry are generally at a high level, and many companies actively take part in and support community activities and stakeholder engagement. Based on this, the industry's sustainability in social issues seems to also be at a relatively good level. The challenges lie in ensuring sufficient benefits for communities in the future and in transparent and proactive communication, which are questions to be addressed by both companies and governance.

Research into the mining industry's ability to buffer economic recessions and the investment activity on the mining industry in Finland was briefly discussed in paper IV. However, this theme is essential in considering the long-term continuation of the industry. On one hand, Finland is currently seen to be a very interesting target for exploration investment, which supports the possibility for long-term continuation of the industry in the country. On the other hand, there appear to be differences in the ability of some mining companies to endure price decreases based on the recent economic challenges in some Finnish mines (HS 2013), although for others these issues seem to set no serious problems (YLE 2013). This could be further studied in the future in terms of economic sustainability at the company and the industry level, and more attention could be paid to it by companies and investors.

Finally, one aspect in the sustainable use of mineral resources is the level of research and development (R&D) in the field (paper II). At its best, R&D improves the environmental and economic feasibility of mines and increases knowledge and understanding of the factors affecting the mining industry on the global scale, as well as its local, national and international effects, in both positive and negative terms. Through its actions in the fields of geology, technology, environmental science, economics and sociology, the mining industry provides an excellent field to perform genuinely multidisciplinary research, which could, at its best, elevate the pursuit of a sustainable mining industry to an entirely new level.

4 Conclusions

In the light of the preceding papers and discussion, the main conclusions relating to the aims of the thesis are as follows:

1. The suitability of different allocation methods in partitioning physical inputs and outputs between mining products in life cycle studies depends on the goal and scope of the study. In general, a decreasing ore grade, and differences in ore grades between products, increases the uncertainty related to allocation. Allocations based on the average product value, or on NMB allocation, are the most suitable methods for studies on production chains. However, mass-based allocation could serve best in studies where mines themselves are compared, for example, at the international level.

2. Governmental research organisations have a triple role in governance, industry and academia: 1) to perform high-level scientific research, especially on applied subjects in their fields of expertise, supporting technological development and knowledge of the functions of society and industrial branches, 2) to provide practical support and expertise for governance and industry, and 3) to aid in data collection and management, and providing support for legislation and planning. In supporting management in the area of mineral resources use, applied knowledge of the quality, location, volume and use of these resources is enhanced. In the context of sustainable development, the role of these organisations is thus to support the government in preventing mineral resource depletion at the national level, and to support industry in striving towards more sustainable practises at mine sites.

3. From the perspective of the international raw material supply chains of the Finnish metals industry, the overall environmental pressure related to mining and transportation is higher abroad than in Finland. This is partly explained by the high share of imported raw materials in the total metallic mineral resources use in Finland, which increases the share of environmental pressures situated abroad, but also by the differences in mining techniques, ore types and energy technologies between source countries. However, the domestic effects are increasing, as the mining industry in Finland has been rapidly developing in recent years towards larger mining operations and poorer ore grades. This growth has potential in bringing socio-economic prosperity to the country, but also increases waste mineral flows, energy use and CO_{2eq} emission levels. This may create continued pressures for justifying the mining activities in the country, especially if the socio-economic benefits are not realised as expected and/or the environmental effects increase noticeably, despite efforts in environmental management and technology.

4. Although many of the Finnish mines are performing relatively well in social, economic and environmental sustainability, there is always room for improvement, and diverse and profound collaboration between governance, academia and industry is needed in reaching towards maximised benefits and minimised drawbacks derived from mining activities. Generally, the main long-term possibilities and challenges in supporting the sustainable development of the mining industry lie in the following:

- Maintaining profitability during economic downturns and securing investments;
- Securing the availability of a skilled local and regional workforce;
- Supporting domestic downstream processing of mining products;
- Succeeding in environmental, and especially water management, as well as mine closure;
- Handling, minimizing and reusing mineral waste materials;
- Increasing energy efficiency;
- Supporting the ability of especially small- and medium-scale exploration and mining companies in taking social responsibility and defining communication strategies;
- Considering the need for reforms in the system of mining taxation, especially benefitting the local communities.

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